CHAPTER 3
AIRWORTHINESS STANDARDS
TRANSPORT CATEGORY ROTORCRAFT

MISCELLANEOUS GUIDANCE (MG)

AC 29 MG 11 FATIGUE EVALUATION OF TRANSPORT CATEGORY ROTORCRAFT STRUCTURE (INCLUDING FLAW TOLERANCE)

a. PURPOSE. This advisory material provides an acceptable means of compliance with the provisions of § 29.571 of the Federal Aviation Regulations (FAR) dealing with the fatigue evaluation of transport category rotorcraft structure (AC 20-95, Fatigue Evaluation of Rotorcraft Structure, May 18, 1976, applies to normal category rotorcraft structure and older transport category rotorcraft). The fatigue evaluation procedures outlined in paragraph AC 29 MG 11 are for guidance purposes only and are neither mandatory nor regulatory in nature. Although a uniform approach to fatigue evaluation is desirable, it is recognized that in such a complex problem, new design features and methods of fabrication, new approaches to fatigue evaluation, and new configurations may require variations and deviations from the procedures described herein. It is recommended that major deviations from the procedures be coordinated with the Rotorcraft Standards Staff, ASW-110, to assure national standardization.

b. SPECIAL CONSIDERATIONS. The structure of rotorcraft is subject to cyclic stresses in practically every regime of flight. In addition, since rotorcraft are highly maneuverable and capable of forward, rearward, sideward, vertical, and rotational flight, operating limitations due to fatigue are possible in practically all flight situations. Corrosion and other environmental damage are also common in rotorcraft operations. For these reasons, special attention should be focused on the fatigue evaluation of rotorcraft structure.

c. BACKGROUND.

(1) During recent years there have been significant state-of-the-art and industry practice developments in the area of structural fatigue and fail-safe strength evaluations of transport category rotorcraft. The advance in the state-of-the-art has resulted from two primary programs: (1) the perfecting of production techniques for composite construction, and (2) the damage tolerant design features required to meet the battle damage requirements of military programs such as the Advanced Attack and Heavy Lift Helicopter (AAH and HLH) programs.

(2) Recognizing that advances in state-of-the-art and industry practice warranted changes to the existing fatigue requirements in Part 29, the regulatory requirements of § 29.571 were substantially revised. The revision to § 29.571 requires new guidance material containing compliance provisions related to the changes. Also, paragraph AC 29 MG 11 supplements AC 20-95 for new transport category rotorcraft and provides guidance material in the flaw tolerance area. General guidance material

for flaw/damage tolerance of composite structures is provided in AC 20-107A, Composite Aircraft Structure, April 25, 1984.

d. INTRODUCTION.

(1) Definitions.

(i) Fatigue Tolerance. The capability of structure to continue functioning without catastrophic failure after being subjected to fatigue (repeated) loads expected during operation of the rotorcraft. Fatigue tolerance may be achieved by safe-life design, flaw tolerant safe-life design (enhanced safe life), fail-safe design considering flaw growth, or a combination.

(A) Safe Life. The capability of pristine structure as shown by tests, or analysis based on tests, not to sustain measurable cracks during the service life of the rotorcraft or before an established replacement time. Special inspection intervals or other special procedures are not usually prescribed for safe-life substantiations. (Routine inspections for wear, fretting, corrosion, crack, and service damage as outlined in § 29.1529 are, of course, appropriate.)

(B) Flaw Tolerant (Enhanced) Safe Life. The capability of flawed structure as shown by tests or analysis based on tests to sustain, without measurable flaw growth, the spectrum of operating loads expected during the service life of the rotorcraft or during an established replacement time. Measurable flaw growth means flaw growth beyond an acceptable threshold of detectability. Enhanced safe life may be achieved by designing structure (single element or multiple element) that provides for resistance to crack initiation from manufacturing or service flaws, by material selection, by material processing, by limitation of stress levels, and by geometric design features. The protection of structure against environmental damage and accidental mechanical damage through the use of protective coatings may be used in determining initial flaw types and sizes to be considered."

(C) Fail-Safe Design Considering Flaw Growth. The capability of rotorcraft structure to continue functioning without catastrophic failure after being subjected to fatigue damage, corrosion, intrinsic flaws, or accidental damage expected during fabrication and operation of the rotorcraft. The concept of fail-safety now includes some discrete damage requirements and more explicitly requires consideration of "life-remaining" after flaws occur until the flaws are detected using a prescribed inspection plan or until the part is replaced. Fail-safe designs may include any of the following features:

(1) Multiple Load Path. Structure providing two or more separate and distinct paths of structure that will carry limit load after complete failure of one of the members.

(i) Active Multiple Load Path. Structure providing two or more load paths that are all loaded during operation to a similar load spectrum. The use of active multiple load paths requires special attention to fatigue damage in the remaining members after failure of a member.

(ii) Passive Multiple Load Path. Structure providing load paths with one or more of the members (or areas of a member) relatively unloaded until failure of the other member or members.

(2) Flaw Arrest (Flaw Stopper) Feature. Structure that does not provide completely separate and distinct load paths but does provide features of design such as bonded and/or riveted straps, changes in geometry, or special processing techniques such as rolling or coining to retard or arrest flaw growth.

(3) Slow Flaw Growth Feature. Structure (single element or multiple element) that provides for slow flaw growth by material selection, material processing, limitation of stress levels, geometrical design features, or by other methods.

NOTE: The detection of the crack or other flaw is an integral part of the flaw growth method. The need to use complicated inspection techniques may not be practical in some cases. See the discussion in paragraph AC 29 MG 11 g(1)(iii)(B).

(ii) Flaw. Structural imperfections in excess of type design allowances for "as manufactured" or "pristine" structure.

(A) In Metallics.

(1) For Fail-Safe Crack Growth. Corner cracks for holes, semicircular cracks for surfaces, realistic cracks for other locations.

(2) For Flaw Tolerance (Enhanced) Safe Life. Gouges, scratches, corrosion, fretting, or wearing likely to occur during fabrication and operation of the rotorcraft.

(B) In Nonmetallics. Flaws should be determined in accordance with AC 20-107A guidance.

(iii) Limit Design Load. "The maximum loads to be expected in service," as defined by § 29.301(a), are considered as limit loads for new structure and as ultimate loads for flaw tolerance residual strength demonstration purposes. The residual strength after failure should equal or exceed these loads for flaw tolerance.

(iv) Damage Tolerance. No definition is provided in paragraph AC 29 MG 11 for this expression because many definitions have been applied by the civil and military communities. The expression has been used to describe design features, structural systems (including design, manufacturing, and operating considerations), and substantiation techniques such as fracture mechanics analyses for metallics. Paragraph AC 29 MG 11 uses expressions for those features of the general damage tolerance concept used to provide and demonstrate fatigue tolerance of rotorcraft structure including consideration of flaws. Tolerance to flaws rather than tolerance to damage is specified in paragraph AC 29 MG 11 since flaws intrinsic to certain manufacturing and fabrication processes are covered in addition to damage from handling, corrosion, etc.

(2) Rotorcraft Flaw Tolerance. Flaw tolerant design as substantiated by fail-safe flaw growth or flaw tolerant (enhanced) safe-life means outlined in § 29.571 and paragraph AC 29 MG 11 g is required, unless it entails such complications that an effective flaw tolerant structure cannot be achieved within the limitations of geometry, inspectability, or good design practice. Good design practice includes consideration of component complexity, component weight, methods of production and component cost. Under these circumstances, a design that complies with safe-life criteria should be used. Typical examples of structure that might not be conducive to flaw tolerance design are swashplates, main rotor shafts, push rods, small rotor head components (i.e., devices, bolts, etc.), landing gear, and gearbox internal parts including bearings. In addition, the need for the use of inspection techniques and equipment or highly trained personnel--resources not available (for economic or other reasons) to the small operator or in remote areas of operation--should be carefully considered (reference paragraphs AC 29 MG 11 d(1)(i)(C)(3) and g(1)(iii)(B)).

(3) Test Background. Experience with the application of methods of fatigue evaluation indicates that a relevant test background should exist in order to achieve the design objective. Even under the flaw tolerance method discussed in paragraph AC 29 MG 11g, it is the general practice within industry to conduct flaw tolerance tests for design information and guidance purposes. Flaw location and flaw growth data based on test results and service history of similar parts, if available, should also be considered in establishing a recommended inspection program.

(4) Manufacturing Considerations. Assurance of structural adequacy also includes manufacturing and fabrication in accordance with design requirements and specifications, quality control to monitor compliance, and effective service inspection procedures.

(5) Fatigue Tolerance Considerations. In the fatigue tolerance evaluation, the following items should be considered:

(i) Identification of the structure to be considered in each evaluation (a failure mode and effects analysis or similar method should be used).

(ii) The stresses and strains (steady and oscillatory) associated with all representative steady and maneuvering operating conditions expected in service.

(iii) The frequency of occurrences of various flight conditions and the corresponding spectrum of loadings and stresses.

(iv) The fatigue strength, fatigue crack propagation characteristics of the materials used and of the structure, and the residual strength of the damaged structure.

(v) Inspectability, inspection methods, and detectable flaw sizes.

(vi) Variability of the measured stresses of paragraph AC 29 MG 11 d(5)(ii), the actual flight condition occurrences of paragraph AC 29 MG 11 d(5)(iii), and the fatigue strength material properties of paragraph AC 29 MG 11 d(5)(iv).

e. FLIGHT STRAIN MEASUREMENT PROGRAM.

(1) General. Subsequent to design analysis, in which aircraft loads and associated stresses are derived, the stress level and/or loads are to be verified by a carefully controlled flight strain measurement program. (This guidance is similar to that of AC 20-95.)

(2) Instrumentation.

(i) The instrumentation system used in the flight strain measurement program should accurately measure and record the critical strains under test conditions associated with normal operation and specific maneuvers. The location and distribution of the strain gages should be based on a rational evaluation of the critical stress areas. This may be accomplished by appropriate analytical means supplemented, when deemed necessary, by strain sensitive coatings or photoelastic methods. The distribution and number of strain gages should define the load spectrum adequately for each part essential to the safe operation of the rotorcraft as identified in § 29.571(a)(1)(i). Other devices such as accelerometers may be used as appropriate.

(ii) The corresponding flight parameters (airspeed, rotor RPM, center of gravity accelerations, etc.) should also be recorded simultaneously by appropriate methods. This is necessary to correlate the loads and stresses with the maneuver or operating conditions at which they occurred.

(iii) The instrumentation system should be adequately calibrated and checked periodically throughout the flight strain measurement program to ensure consistent and accurate results.

(3) Parts to be Strain-Gauged. Fatigue critical portions of the rotor systems, control systems, landing gear, fuselage, and supporting structure for rotors, transmissions, and engine are to be strain-gauged. For rotorcraft of unusual or unique design, special consideration might be necessary to ensure that all the essential parts are evaluated.

(4) Flight Regimes and Conditions to be Investigated.

(i) Typical flight and ground conditions to be investigated in the flight strain measurement program are given in Attachment 1 to paragraph AC 29 MG 11.

(ii) The determination of flight conditions to be investigated in the flight strain measurement program should be based on the anticipated use of the rotorcraft and, if available, on past service records for similar designs. In any event, the flight conditions considered appropriate for the design and application should be representative of the actual operation in accordance with the rotorcraft flight manual. In the case of multiengined rotorcraft, the flight conditions concerning partial engine-out operation should be considered in addition to complete power-off operation. The flight conditions to be investigated should be submitted in connection with the flight evaluation program.

(iii) The severity of the maneuvers investigated during the flight strain survey should be at least as severe as the maximum likely in service.

(iv) All flight conditions considered appropriate for the particular design are to be investigated over the complete rotor speed, airspeed, center of gravity, altitude, and weight ranges to determine the most critical stress levels associated with each flight condition. The temperature effects on loads as affected by elastomeric components are to be investigated. To account for data scatter and to determine the stress levels present, a sufficient amount of data points should be obtained at each flight condition. Consideration can be given to the use of scatter factors in determining the sufficiency of data points. In some instances, the critical weight, center of gravity, and altitude ranges for the various maneuvers can be based on past experience with similar design. This procedure is acceptable where adequate flight tests are performed to substantiate such selections. The combinations of flight parameters that produce the most critical stress levels should be used in the fatigue evaluation.

f. FREQUENCY OF LOADING.

(1) Types of Operation.

(i) The probable types of operation (transport, utility, etc.) for the rotorcraft should be established. The type of operation can have a major influence on the loading environment. In the past, rotorcraft have been substantiated for the most critical general types of operation with some consideration of special, occasional types of operation. To assure that the most critical types of operation are considered, each major rotorcraft structural component should be substantiated for the most critical types of operation as established by the manufacturer. The types of operation shown below should be considered and, if applicable, used in the substantiation:

(A) Long flights to remote sites (low ground-air-ground cycles but high cruise speeds).

(B) Typical, general types of operation.

(C) Short flights as used in logging operations.

(ii) One means is to substantiate for the most severe type of operation; however, this method is not always economically feasible.

(iii) A second means is to quantify the influence of mission type on fatigue damage by adding to or replacing hour limitations by flight cycle limitations (if properly defined and easily identifiable by the crew, for example: one landing, one load transportation). A special type of flight hour limitation replacement using factorization of flight hours for multiple types of operations may be feasible if continuing manufacturers' technical support is provided and documented; i.e., the manufacturer either provides the factorization analyses or checks them on a continuing basis for each rotorcraft.

(iv) Where one or more of the above operations are not among the general uses intended for the rotorcraft, the rotorcraft flight manual should state in the limitations section that the intended use of the rotorcraft does not include certain missions or repeated maneuvers (i.e., logging with its high number of takeoffs/landings per hour). A note to this effect should also appear in the rotorcraft airworthiness limitations section of the maintenance manual prepared in accordance with § 29.1529.

(v) Should subsequent usage of the rotorcraft encompass a mission for which the original structural substantiation did not account, the effects of this new mission environment on the frequency of loading and structural substantiation should be addressed and where practicable, in the interest of safety, a reassessment made. If this reassessment indicates the necessity for revised retirement times, those new times may be limited to aircraft involved in the added mission provided--

(A) Proper part reidentification is established;

(B) A Rotorcraft Flight Manual (RFM) supplement outlining limitations is approved;

(C) An airworthiness limitations section supplement is approved; or

(D) An appropriate combination of part reidentification, RFM supplement, or airworthiness limitation section supplement is approved.

(2) Loading Spectrum. The spectrum allocating percentage of time or frequencies of occurrence to flight conditions or maneuvers is to be based on the expected usage of the rotorcraft. This spectrum is to be such that it is unlikely that actual usage will subject the structure to damage beyond that associated with the

spectrum. Considerations to be included in developing this spectrum should include prior knowledge based on flight history recorder data, design limitations established in compliance with § 29.309, and recommended operating conditions and limitations specified in the rotorcraft flight manual. The distribution of times at various forward flight speeds should reflect not only the relation of these speeds to V_{NE} but also the recommended operating conditions in the rotorcraft flight manual that govern V_c or cruise speed. Where possible, it is desirable to conduct the flight strain-gage program by simulating the usage as determined above, with continuous recording of stresses and loads, thus obtaining directly the stress/load spectra for structural elements.

g. FATIGUE STRENGTH EVALUATION (INCLUDING ROTORCRAFT FLAW TOLERANCE).

(1) General. A means should be established using the conventional safe-life approach or another fatigue tolerant approach to control the airworthiness of principal structural elements identified under § 29.571(a)(1)(i). While the conventional safe-life approach is acceptable under certain circumstances as defined in § 29.571, the enhanced safe-life and fail-safe flaw growth approaches are to be used unless shown to be impractical as stated in § 29.571. A fatigue strength evaluation of structure considering tolerance to flaws is intended to ensure that even when flaws are present due to manufacturing of service operations, the structure will withstand service loads without failure until the flawed parts are replaced or until the flaws (including resulting fatigue cracks) are detected and appropriate action taken. Either of two types of fatigue strength evaluation may be used for flaw tolerance substantiation: flaw tolerant (enhanced) safe-life or fail-safe flaw growth methods. Flaw tolerant (enhanced) safe-life includes the testing and analyses currently associated with safe-life substantiation, plus consideration of flaws. Flaw growth methods include the testing and analyses currently associated with damage tolerance assessment (DTA). Tests are required to substantiate flaw propagation rates and residual strength. Either method or a combination can be used to meet the requirements of § 29.571 for tolerance to flaws. Flaw tolerance evaluation encompasses establishing the components to be designed as flaw tolerant, defining the loading conditions and extent of flaws for which the structure is to be designed, conducting structural tests and analyses to substantiate that the design objectives have been achieved, and establishing replacement times or establishing inspection programs as necessary to assure detection of fatigue damage. On components predominantly loaded by centrifugal force, care should be taken in selecting limit load to assure that it is the maximum expected in service. Design features that should be used in attaining a flaw tolerant structure are:

(i) Use of multi-path construction and the provision of crack stoppers to limit the growth of cracks and to provide adequate residual strength.

(ii) Selection of materials and stress levels that preclude crack growth from flaws or that provide a controlled slow rate of crack propagation combined with high residual strength after initiation of cracks. Tests are required to substantiate crack propagation rates.

(iii) Design to permit detection of cracks and other flaws, including the use of crack detection systems, in all critical structural elements before cracks can propagate and become dangerous or result in appreciable strength loss and to permit replacement or repair. Inspection means appropriate for flaw tolerant design follow:

(A) Routine Inspections. To support routine inspection programs, blind areas should be avoided, where practical. Access panels and openings should be considered early in design.

(B) Special Inspections. These inspections will generally result from test results as well as the geometry of the design. Care should be given to special inspection techniques to be used in the field. Inspection techniques requiring facilities and resources beyond the capability of the small operator or not generally available in remote-area operations traditionally associated with rotorcraft operations should not be specified for field inspections. Conservative sizes for detectable cracks or other flaws should be used. Sufficient interval inspections should be provided to detect cracks before they grow from a detectable size to a size that reduces the remaining strength below design limit strength. If special inspection techniques not commonly available cannot be avoided, then use of enhanced safe-life substantiation techniques should be used.

(C) Pressurized Chambers. This design feature may be used to detect cracks that cause a chamber to lose its pressure (either positive or negative). The loss of pressure can be indicated by gages, or dye may be used if it is shown to be a dependable indicator. Care should be taken in the design of pressurized chambers and their indicating systems to assure dependability. Undependable systems can cause an inordinate number of false indications and maintenance problems.

(D) Vibration Generation. This characteristic should be considered both from the aspect of vibrations giving indications of a failure and from the aspect of the increased fatigue loading resulting from the vibrations.

(E) Noise Generation. If initial failure will result in a clear and unmistakable noise that is sufficiently continuous and loud, this characteristic can be used in achieving flaw tolerance without additional special inspections.

(F) Crack Detection Wire, Foil, etc. Detection wire may be used in areas that are sufficiently well defined so that the wire can be properly located. This technique is appropriate in areas otherwise difficult to inspect. The potential for false readings and possible maintenance problems should be considered.

(G) Health Monitoring. Techniques such as vibration sensing and analysis or real time oil analysis can be used to provide information on establishing inspection time.

(iv) Use of multiple element structures may be provided so that damage or failure occurring in one element of the member will be confined to that element and the remaining structure will still possess adequate load-carrying ability until the failed element is discovered by inspection.

(v) Provisions to limit the probability of concurrent multiple damage, particularly after long service, should be provided. These provisions should ensure adequate independence of each failure mode of multi-path constructions. The use of full-scale fatigue test articles are recommended in this evaluation. Examples of concurrent multiple damage to be avoided are:

(A) Simultaneous failure or partial failure of multiple path discrete elements working at similar stress levels.

(B) Failures or partial failures, in adjacent areas, due to redistribution of loading following a failure of a single element.

(2) Identification of Principal Structural Elements. Principal structural elements are those that contribute significantly to carrying flight and ground loads and whose failure could result in catastrophic failure of the rotorcraft. Typical examples of such elements are:

(i) Rotor blades and attachment fittings.

(ii) Rotor heads, including hubs, hinges, and some main rotor dampers.

(iii) Control system components subject to repeated loading, including control rods, servo structure, and swashplates.

(iv) Rotor supporting structure (lift path from airframe to rotor head).

(v) Fuselage, including stabilizers and auxiliary lifting surfaces.

(vi) Main fixed or retractable landing gear and fuselage attachment structure.

(3) Identification of Locations Within Principal Structural Elements to be Evaluated. The locations of damage to structure for damage tolerance evaluation can be determined by analysis or by fatigue test on complete structures or subcomponents. However, tests will be necessary when the basis for analytical prediction is not reliable, such as for complex components. If less than the complete structure is tested, care should be taken to ensure that the internal loads and boundary conditions are valid.

(i) The following should be considered:

(A) Strain gage data on undamaged structure to establish points of high stress concentration as well as the magnitude of the concentration;

(B) Locations where analysis shows high stress or low margins of safety;

(C) Locations where permanent deformation occurred in static tests;

(D) Locations of potential fatigue damage identified by fatigue analysis;

(E) Locations where the stresses in adjacent elements will be at a maximum with an element in the location failed;

(F) Partial fracture locations in an element where high stress concentrations are present in the residual structure;

(G) Locations where detection would be difficult;

(H) Design details that service experience of similarly designed components indicates are prone to fatigue or other damage; and

(I) Components fabricated from materials of potentially low fracture toughness or high flaw growth rate.

(ii) In addition, the areas of probable damage from sources such as a severe corrosive and/or fretting environment, a wear and/or galling environment, or a high maintenance environment should be determined from a review of the design and past service experience.

(4) Extent of Flaws. Each particular design should be assessed to establish appropriate damage criteria in relation to inspectability and flaw extension characteristics. In any flaw determination, it is possible to establish the extent of flaws in terms of detectability with the inspection techniques to be used, the associated single element failure or initially detectable flaw size, the residual strength capabilities of the structure, and the likely flaw extension rate (after either an element failure or a partial failure) considering the expected stress redistribution under the repeated loads expected in service and with the expected inspection frequency. Although multiple-element design should be used where practical, and obvious partial failure could be considered to be the extent of the flaw for residual strength assessment, provided a positive determination is made that manufacturing or service flaws will not initiate flaw growth within the life of the part or that the fatigue flaw growth will be detectable by the available inspection techniques at a sufficiently early stage of the flaw growth. In a swashplate or pin containing pressurized chamber, an obvious partial failure might be detectable through the inability of the chamber to maintain pressure after occurrence of the damage. Flaw tolerant (enhanced) safe-life evaluations from flaws should consider flaws to be expected during manufacturing (including handling) and during service. Special coatings against corrosion, flame plating or plasma plating

against fretting corrosion, and energy absorption coating or shielding against damage associated with maintenance may be used in determining the type and extent of flaws to be considered in flaw tolerant (enhanced) safe-life evaluations. The following are typical examples of the type of partial failures that may be considered in the flaw growth fail-safe and enhanced safe-life evaluation. These may or may not be appropriate to the design being considered. These examples have been sources of service difficulty on prior/existing designs:

(i) Detectable skin cracks in the trailing edge sections of rotor blades.

(ii) Detectable failures of individual straps in "strap packs."

(iii) Detectable skin cracks emanating from the edge of structural openings or cutouts;

(iv) Detectable circumferential or longitudinal skin crack in the basic fuselage or tail boom structure;

(v) Complete severance of interior frame elements or stiffeners in addition to a detectable crack in the adjacent skin;

(vi) Presence of a detectable fatigue failure in at least the tension portion of the spar web or similar element;

(vii) Detectable failure of a primary attachment, including blade attachment fittings and control surface hinge and fittings; and

(viii) Fretting, corrosion, and galling conditions expected in service.

(5) Provisions for Inspection. The designer should strive to ensure adequate inspectability of all structural parts to qualify them under the fail-safe flaw growth provisions. In those cases where blind areas or surfaces exist, suitable design features should be provided to allow inspection techniques (either visual or nondestructive testing, as necessary) to assure adequate residual strength is achieved unless shown to be impractical due to limitations of geometry and good design practice. In addition, the alternate safe-life approach to fatigue tolerance should be implemented if the inspection techniques are shown to be too complicated and impractical.

(6) Testing of Principal Structural Elements. The nature and extent of tests on complete structures or on portions of the primary structure will depend upon applicable previous design, construction, tests, and service experience in connection with similar structures. For flaw tolerant safe-life testing, simulated flaws should be as representative as possible of actual gouges, scratches, pitting, or fretting to be expected in manufacture and service. For fail-safe testing considering crack propagation, simulated cracks should be as representative as possible of actual fatigue damage. Where it is not practical to produce actual fatigue cracks, flaws can be

simulated by cuts made with a fine saw, sharp blade, guillotine, or other suitable means. The validity of saw cuts, etc., should be verified by comparison to coupon tests of a cracked specimen of the same material. In those cases where bolt failure, or its equivalent, is to be simulated as part of a possible flaw configuration in joints or fittings, bolts can be removed to provide that part of the simulation.

(7) <u>Flaw Tolerance Demonstration (Flaw Tolerant (Enhanced) Safe-Life or Fail-Safe Flaw Growth)</u>.

(i) It should be determined by analysis, supported by test evidence, that the structure with the extent of damage established for residual strength evaluation can withstand the specified design limit loads (considered as ultimate loads). Flaw tolerant safe-life substantiation provides a safe period of operation of structure with flaws with only routine inspections necessary. Safe crack growth (fracture mechanics) substantiation for fail-safe designs, on the other hand, provides for limited operation after crack initiation from flaws until the cracks can be safely detected. Since flaw tolerant safe life does not provide for detailed crack growth beyond the threshold of detectability, it will tend to apply to life-limited parts, particularly those hard to inspect. Safe crack growth substantiation of fail-safe designs is applicable to readily inspectable parts and may provide for replacement “on condition” rather than at a specified life.

(ii) The enhanced safe-life of metallic components will use analyses and testing similar to that of basic safe-life except that “flawed” specimens will be tested rather than “pristine” specimens.

(A) In order to determine the mean fatigue strength and the variability in fatigue strength considering flaws, it is necessary to test a number of specimens in establishing stress versus number of cycles (S-N) curves. Both full-scale and coupon specimens may be used to account for the variability in fatigue strength. A reduction factor should be applied to the mean curve in arriving at a working S-N curve. This factor should include consideration of the number of specimens tested, the variability of the fatigue results and, where available, previous test data on the same materials or similar components, as well as service experience.

(B) Where new materials or designs are being evaluated, it is recommended that a larger reduction factor be used until additional test data justifying a change are available. The mean and reduced S-N data acceptable to the Administrator on specimens with stress concentration factor, as applicable. A reduced S-N curve and the loading spectrum of paragraph AC 29 MG 11 f(2) should be used in determining replacement times.

(C) Figure AC 29 MG 11-1 represents the method of constructing a typical S-N curve from the fatigue test data. Four to six full-scale specimens have commonly been used in past safe-life programs to determine mean S-N curves. The applicant may propose a specific number of specimens that may be evaluated with respect to the proposed methodology in determining the acceptability of the structural substantiation program.

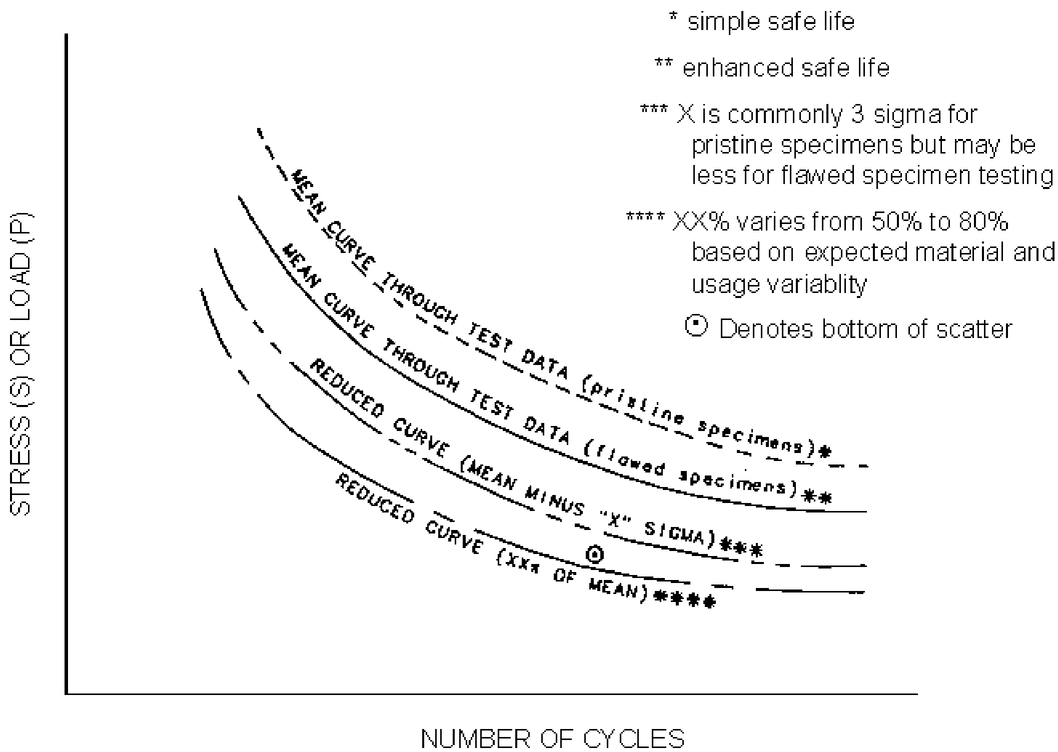

FIGURE AC 29.MG 11-1 S-N OR P-N CURVE USAGE

(D) Additional coupon tests have been used, when necessary, to identify more completely test scatter due to material properties variability. When the agreed-upon number of specimens is tested at various acceptable load levels, a reduction by three mean standard deviations, sigma (σ), necessary to account for material properties, should be made to establish a reduced S-N curve for determination of retirement times. This reduction may take into account the fact that flawed specimens were tested to preclude a dual penalty situation. Reduction by two mean standard deviations rather than three, may be used if justified by appropriate design features such as multiple elements or unmistakable flaw indications or by material properties that provide benign types of failure modes.

(E) "Run-outs" (specimens that do not fail) may be treated in one of three ways: deleted from data (conservative), considered as a failure at maximum test cycles (conservative), or considered in a rational manner to develop a more realistic "σ." To further account for variability in fatigue strength not totally accounted for by this reduction in S-N data, the lesser of this reduction, 80 percent of mean, or bottom of scatter, may be used as a limit, where justified, depending on material properties.

(iii) The procedures in Paragraph 7a of AC 20-107A provide criteria for substantiating safe flaw growth for composite structure.

(iv) Safe crack growth (fracture mechanics) substantiation should show that the damage growth rate under the repeated loads expected in service (between the time at which the damage becomes initially detectable and the time at which the extent of damage reaches the value for residual strength evaluation) provides a practical basis for development of the inspection programs and procedures described in paragraph AC 29 MG 11g(8). For multiengine load paths, a minimum of three inspection intervals is recommended between the initially detectable damage time and the time when residual strength is reduced to design limit load by crack growth. For single element structures, a minimum of four inspection intervals is recommended. The repeated loads should be defined in the loading, temperature, and humidity spectra. The loading conditions should take into account the effects of structural flexibility and rate of loading where it is significant.

(v) For flaw tolerance to achieve an improvement in safety over safe-life for composite structures, the procedures of Paragraph 7a of AC 20-107A are recommended. For flaw tolerance to achieve and improvement in safety over simple safe-life for metallic structures, the following testing criteria are recommended to supplement flaw tolerant safe-life analysis using flawed specimen S-N curves or crack growth analyses using appropriate stress intensity factors and da/dn data from coupon tests:

(A) <u>Flaw Tolerant (Enhanced) Safe-Life Testing Criteria</u>. Test full-scale specimens with flaws or a mix of full-scale and coupon specimens with flaws to obtain S-N data. Plot the data as shown in figure AC 29 MG 11-1. Utilize the S-N data and loading spectrum of paragraph AC 29 MG 11 f(2) in substantiating a crack-free life or in arriving at a replacement time by cumulative damage analysis means. Where practical (as allowed by the number of damaging cycles in the loading spectrum), spectrum testing may be used for fatigue substantiation in lieu of S-N testing followed by analysis. The replacement time established should be included in the airworthiness limitations section of the document established under § 29.1529.

(B) Fail-Safe Crack Growth (Fracture Mechanics) Substantiation. Test two or more specimens to obtain crack propagation data using either a realistic load spectrum or an accelerated load (spectrum or single) associated with the use of propagation theory and data after cracks have been initiated. Unless a more rational method with an equivalent level-of-safety is applied for, the following methods of setting inspection intervals should be applied. In all cases, the inspection methods and intervals should adequately consider variables such as inspectability, type of inspection, crack growth behavior, and other scheduled maintenance considerations.

(1) For single element (load path) structure, plot the data and set the inspection as shown in figure AC 29 MG 11-2.

(i) Set the initial inspection at $L_1/3$.

(ii) Set the repetitive inspection intervals at $L_2/4$.

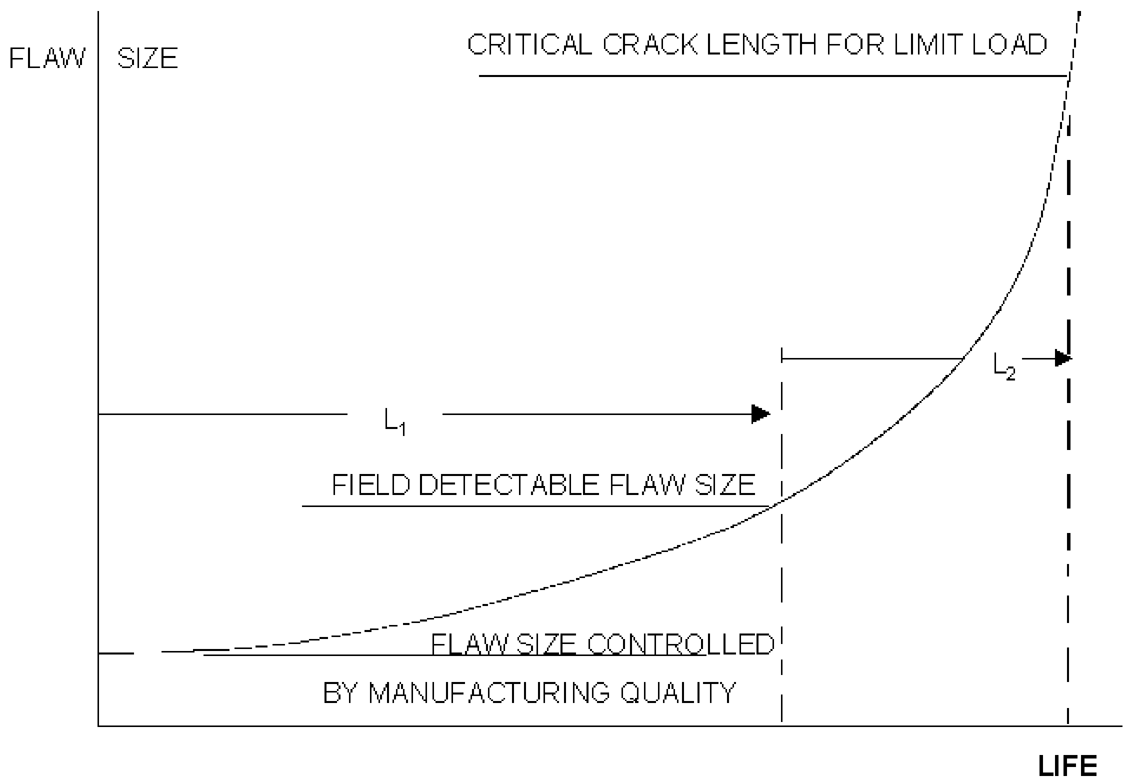

FIGURE AC 29.MG 11-2 CRACK GROWTH FOR SINGLE ELEMENT STRUCTURE

(2) For multi-element load path structure:

(i) Test all paths simultaneously with a 0.05-inch thick crack (or size detectable by manufacturing quality control procedures) in the critical element at the start of tests.

(ii) Note when field detectable cracking occurs.

(iii) Note when one element fails.

(iv) Note when the residual strength of the remaining elements decreases to limit load due to crack growth.

(v) From figure AC 29 MG 11-3, set initial inspection at $L_1/3$.

(vi) Set repetitive inspection intervals at $(L_2 + L_R)/3$.

NOTE: If partial failure of the critical element is not detectable, then L_2 becomes zero.

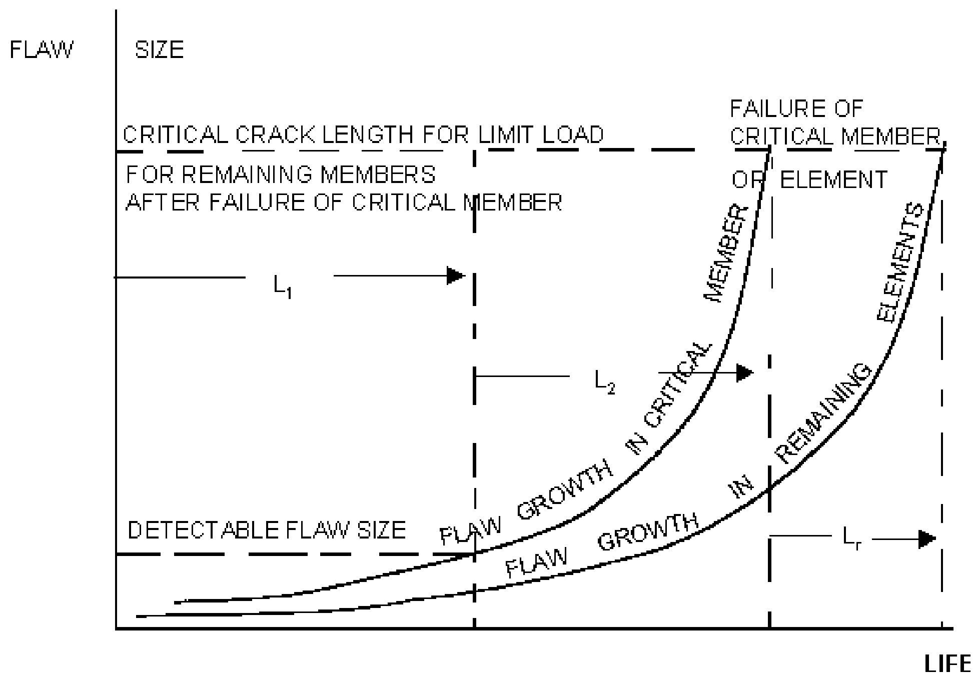

FIGURE AC 29MG 11-3 CRACK GROWTH FOR REMAINING ELEMENTS
OF MULTIPLE ELEMENT STRUCTURE

(C) Other test and inspection programs may be used rather than those of paragraph AC 29 MG 11 g(7)(v)(A) and paragraph AC 29 MG 11 g(7)(v)(B), if shown to have comparable or better probability of assuring that a catastrophic fatigue failure will not occur.

(vi) The flaw tolerance characteristics can also be shown analytically by reliable or conservative methods such as the following:

(A) By demonstrating quantitative relationships with structure already verified as damage tolerant;

(B) By demonstrating that the damage would be detected before it reaches the value for residual strength evaluation; or

(C) By demonstrating that the repeated loads and limit load stresses do not exceed those of previously verified designs of similar configuration, materials, and inspectability.

(8) Inspection. Detection of flaws before they become dangerous is the ultimate control in ensuring the flaw tolerance characteristics of the structure. Therefore, the applicant should provide sufficient guidance information to assist operators in establishing the frequency, extent, and methods of inspection of the critical structure, and this kind of information should, under § 29.571(a)(2), be included in the maintenance manual required by § 29.1529. Due to the inherent, complex interactions of the many parameters affecting flaw tolerance, such as operating practices, environmental effects, load sequence on flaw growth, and variations in inspection methods, related operational experience should be taken into account in establishing inspection procedures. Comparative analysis can be used to guide the changes from successful past practice, when necessary. Therefore, maintenance and inspection requirements should recognize the dependence on experience and should be specified in a document that provides for revision as a result of operational experience, such as the one containing the operator's FAA/AUTHORITY-approved structural inspection program developed through the Maintenance Review Board (MRB) procedures for FAR Part 121 operators.

h. COMBINATION OF REPLACEMENT TIME AND FLAW GROWTH EVALUATION. It may be possible to extend the replacement time of safe-life components that exhibit limited flaw tolerance capability by using a combination of the safe-life and flaw growth characteristics as described elsewhere in paragraph AC 29 MG 11 and by assigning both a replacement time and inspection period to these components. The replacement time may then be based on the combined probability of not initiating a fatigue crack at or before the replacement time and the probability that the crack, if initiated, will be detected prior to catastrophic failure or loss of limit load (or maximum attainable load, whichever is less) carrying capability. The probability of detection should be based on consideration of the inspection effectiveness, the inspection intervals, and the fatigue life remaining after an obvious partial failure. A lower strength reduction factor commensurate with this probability of detection may then be used in the determination of the replacement time.

Attachment 1 to AC 29 MG 11
FLIGHT STRAIN PROGRAM CONDITIONS TO BE INVESTIGATED

1. GROUND CONDITIONS.
   a. Normal start.
   b. Rapid increases of RPM on ground to maximum power-on RPM of main rotor.
   c. Taxiing with full cyclic control.
   d. Landing run (if applicable).
   e. Braking (if applicable).
   f. Normal shutdown.
   g. Special ground checks (if applicable).

2. IN-GROUND-EFFECT (IGE) MANEUVERS.

   a. Hovering.

      (1) Steady with rotor at maximum side of RPM tolerance.
      (2) Steady with rotor at minimum side of RPM tolerance.
      (3) 90° right turn.
      (4) 90° left turn.
      (5) Control reversal.
         (i) Longitudinal.
         (ii) Lateral.
         (iii) Rudder.
      (6) Sideward flight.
         (i) Right.
         (ii) Left.
         (iii) Rearward flight.

   b. Maneuvering.

      (1) Jump takeoff.
      (2) Normal takeoff and accelerate to climb airspeed.
      (3) Normal approach and landing.
         (i) Multiengine.
         (ii) One-engine-inoperative.
      (4) Full autorotational landing.

Attachment 1 to AC 29 MG 11
FLIGHT STRAIN PROGRAM CONDITIONS TO BE INVESTIGATED
(continued)

3. FORWARD FLIGHT-POWER ON.

a. Level flight.

(1) 40 percent V_H.
(i) Minimum side of main rotor RPM tolerance (RPM +)
(ii) Maximum side of main rotor RPM tolerance (RPM -)
(2) 60 percent V_H.
(i) (RPM +)
(ii) (RPM -)
(3) 80 percent V_H.
(i) (RPM +)
(ii) (RPM -)
(4) V_H.
(i) (RPM +)
(ii) (RPM -)
(5) V_{NE}.
(i) (RPM +)
(ii) (RPM -)

b. Maneuvers.

(1) Full power climbs.
(i) All engines operative.
(ii) One-engine-inoperative.
(2) Cyclic pull-ups.
(i) 60 percent V_H.
(ii) 90 percent V_H.
(3) Normal acceleration from climb airspeed to 90 percent V_H.
(4) Turns.
(i) Right at 60 percent V_H and 90 percent V_H.
(ii) Left at 60 percent V_H and 90 percent V_H.
(5) Control reversals at 90 percent V_H.
(i) Longitudinal.
(ii) Lateral.
(iii) Rudder.
(6) Deceleration from 90 percent V_H to descent airspeed.
(7) Part power descent.
(i) All engines.
(ii) One engine out.

Attachment 1 to AC 29 MG 11
FLIGHT STRAIN PROGRAM CONDITIONS TO BE INVESTIGATED
(continued)

4. POWER TRANSITIONS.

a. All engines operating to one engine out.
(1) In full power climb.
(2) At 90 percent V_H.

b. One engine out to all engines operating in powered descent.

c. All engines operating to autorotation.
(1) At 60 percent V_H.
(2) At maximum forward transition speed.

d. Stabilized autorotation to all engines operating at normal autorotation airspeed.

5. AUTOROTATION.

a. Stabilized.
(1) At 70 percent V_{NE}.
(2) At $_{NE}$.

b. Turns at 70 percent and 100 percent V_{NE}.
(1) Right.
(2) Left.

c. Cyclic pull-up.

d. Control reversals.
(1) Longitudinal.
(2) Lateral.
(3) Rudder.

The flight and ground conditions of this table may be used as practical in developing operating load spectra for the range of projected aircraft usage such as:

(1) Short missions with high-power cycles and ground-air-ground (GAG) cycles (such as used in logging operations).

(2) Medium range missions of 1 to 2 hours that include three or more GAG or LO-HI power cycles per mission.

Attachment 1 to AC 29 MG 11
FLIGHT STRAIN PROGRAM CONDITIONS TO BE INVESTIGATED
(continued)

(3) Long range missions that consider the longest practical range of the aircraft and consider two or more GAG (or high power) cycles per mission (such as used for remote offshore drilling platforms).

If aircraft usages that produce a large number of high-power cycles (approximately 50 per hour) or high GAG cycles (approximately 25 per hour) such as logging operations are not included in the fatigue tolerance substantiation, this should be noted in the RFM and Maintenance Manual airworthiness limitations section (reference paragraph AC 29 MG 11 f(1)).